Helicon Modes Driven by Ionospheric O^+ Ions in the Plasma Sheet Region

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ABSTRACT

It is shown that the presence of ionospheric-origin oxygen ion beams with anisotropic pressure can excite helicon modes in the near-Earth plasma sheet region provided their Alfvénic Mach numbers lie in a certain range. The helicon modes are easily excited under the conditions when the usual long wavelengths fire-hose modes are stable. The typical real frequencies of the excited helicon modes are between 1 to 10 mHz, and the typical e-folding time of the instability is about 3 to 15 minutes at wavelengths of 1 to 5 R_E. Therefore these modes are likely to attain saturation during enhanced convection events lasting for a few hours. Large amplitude helicon modes would distort the ambient magnetic field and may be observable as flux ropes. Low-frequency turbulence produced by these modes could scatter electrons and help excitation of the ion tearing modes leading to substorm onset.

1. INTRODUCTION

Recent observations suggest that ionospheric-origin O^+ ions consititute an important and some times dominant part of the outer magnetosphere and the near-Earth plasma sheet region [*Peterson et al.*, 1981; *Sharp et al.*, 1981; *Lennartsson*, 1994; *Shelley et al.*, 1982; *Hultqvist*, 1991; *Lennartsson and Shelley*, 1986; *Daglis et al.*, 1991, 1993, 1994]. Observations by GEOTAIL, indicate the presence of tailward flowing energetic O^+ ion bursts in the distant magnetotail [*Wilken et al.*, 1995]. Two most important ionospheric outflow regions for the O^+ ions are the auroral region and the dayside cleft [*Lockwood et al.*, 1985; *Yau et al.*, 1986; *Delcourt et al.*, 1989; *Cladis and Francis*, 1992]. Recently, it has been shown that the auroral ionospheric ion feeding of the inner plasma sheet during substorms can be fast (i.e., ~ characteristic substorm timescales), and that the ionosphere could actively influence the substorm energization processes by responding to the increased solar wind-magnetosphere coupling [*Daglis and Axford*, 1996].

Oxygen ions extracted from the ionosphere either from the cusp or auroral region first travel along the lobe field lines close to the plasma sheet or in the plasma sheet boundary layer, until their encounter with the neutral sheet where they are accelerated to higher energies up to several tens of keV [*Sharp et al.*, 1981; *Candidi et al.*, *Möbius et al.*, 1987, *Cladis and Francis*, 1992]. There can also be direct injection of relatively nigh energy (50 100 keV) ionospheric ions from the auroral ionosphere into the near-Earth magnetotail during substorms [*Daglis et al.*, 1994] In this process the outflowing ionospheric ions move along auroral field lines mapping equatorially to the inner plasma sheet. In any case, the ionospheric O^+ ion flux in the near-Earth plasma sheet ($X \sim$ -6R_E to -15 R_E) are observed to increase (dramatically during the growth phase of substorms [*Daglis et al.*, 1990, 1991; *Kistler et al.*, 1992], and hence it could influence the dynamical evolution of the plasma sheet.

It has been suggested that enhanced densities of ionospheric O^+ ions in some localized region in the plasma sheet would favor the excitation of the ion tearing instability [*Schindler*, 1974; *Baker et al.*, 1982], velocity shear instabilities [*Cladis and Francis*, 1992], or firehose type instabilities [*Hill and Voigt*, 1992; *Verheest and Lakhina*, 1991; *Lakhina*, 1995, 1996], which could lead to the onset of the substorms. Thus, it is important to undersand the role of ionospheric O^+ ions on the stability and dynamics of the near-Earth plasma sheet which ultimately controls the substorm processes.

in this paper we have shown that the presence of anisotropic ionospheric-origin O^+ ion beams can excite the helicon mode in the near-Earth ($X \approx$ -10 R_E to -15 R_E) plasmasheet region. in an electron-proton plasma, the dispersion relation for the right hand polarized low-frequency modes, i.e., $w << \Omega_p$ (here w and Ω_p represent the wave, and the proton cyclotron frequencies), propagating parallel to the magnetic field, $\mathbf{B}_0$, gives the MHD Alfvén modes. In this case the proton Hall current completely cancels the electron Hall current, and the wave is maintained by the proton polarization current [*Papadopoulos et al*, 1994]. However, in the presence of oxygen ions, the ion (both proton and oxygen) Hall currents cannot completely cancel the electron Hall current unless $w << \Omega_o$ (Ω_o being the oxygen ion cyclotron frequency). Therefore for the case when O^+ ions are weakly magnetized or unmagnetized, they carry negligible Hall current, and the resultant ion Hall current is not sufficient to neutralize the electron Hall current. This situation could give rise to helicon waves [*Papadopoulos et al.*, 1994; *Zhou et al.*, 1994]. We shall show, for the first time, the possibility of driving the helicon mode instability in the magnetotail by the ionospheric-origin oxygen ion beams. It has been suggested that helicon waves could lead to the fast current and flux penetration across the plasma sheet [*Papadopoulos et al.*, 1994], thus affecting the substorm dynamics. Further these modes may contribute to the observed electromagnetic noise in the ULF - ELF frequency range in the magnetotail [*Russell*, 1972; *Tsurutani et al*, 1985, 1987; *Bauer et al.*, 1995].

2. HELICON MODE INSTABILITY

The dispersion relation for the electromagnetic modes propagating parallel to the magnetic field, $\mathbf{B}_0 = B_0\mathbf{x}$ in a multispecies plasma can be written [*Lakhina*, 1995], in standard notation,

$$\omega^2 = c^2k^2 - \sum_j \omega_{pj}^2 \left[\frac{\omega - kU_j}{k\alpha_{\parallel j}} Z(\eta_j) + \left(\frac{\alpha_{\perp j}^2}{\alpha_{\parallel j}^2} - 1\right)\left(1 + \eta_j Z(\eta_j)\right)\right], \tag{1}$$

where $\omega_{pj} = (4\pi q^2 N_j/m_j)^{1/2}$ and $\Omega_j = q_j B_0/m_j c$ are the plasma and the gyrofrequency of the jth species, with $j = e, p$ and o for electrons, protons and the oxygen ions respectively, U_j is the drift velocity of the jth species, and $\alpha_{\perp j}$ and $\alpha_{\parallel j}$ are respectively the perpendicular and parallel thermal velocities with respect to $\mathbf{B}_0$, and $Z(\eta_j)$ is the well known plasma dispersion function with the argument $\eta_j = (w - kU_j \pm \Omega_j)/k\alpha_{\parallel j}$. The $\pm$ sign in η_j denotes the RH (+ sign) and the LH (− sign) modes. In writing (1), we have taken the distribution functions' as drifted bi-Maxwellians. In the equilibrium state, the charge neutrality is maintained by taking $N_e = N_p + N_O$, where N is density.

For the case of $\eta_j >> 1$ for each species, (1) can be simplified to,

$$
\begin{aligned}
\omega^2 &= c^2k^2 + \sum_j \omega_{pj}^2 \frac{\omega - kU_j}{\omega - kU_j \pm \Omega_j} \Bigg[\\
&\quad + \frac{(\alpha_{\perp j}^2 - \alpha_{\parallel j}^2)k^2}{2(\omega - kU_j \pm \Omega_j)^2}\Bigg].
\end{aligned} \tag{2}
$$

Note that lighter electrons maintain charge and current neutrality in equilibrium but contribute little to the mass average. We consider the case where $(\omega - kU_j)^2 << \Omega_j^2$ for $j = e$ (electrons) and p (protons), and $\omega^2 << c^2$ and take $U_p = 0$ (i. e., proton rest frame), then (2) can be written as

$$
\begin{aligned}
\omega^2 \pm \frac{N_o}{N_p}\Omega_p\omega &- k^2V_{Ap}^2\left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right) - \frac{N_o}{N_p}\frac{\Omega_p\Omega_o(\omega - kU_o)}{\omega - kU_o \pm \Omega_o} \\
&+ \frac{A_o k^2 V_{Ap}^2}{2}\frac{\Omega_o^2}{(\omega - kU_o \pm \Omega_o)^2} = 0.
\end{aligned} \tag{3}
$$

Here pressure anisotropy of the plasma species is represented by $A_j = (\beta_{\parallel j} - \beta_{\perp j})$, where $\beta_{\parallel j}$ and $\beta_{\perp j}$ are respectively the parallel and the perpendicular plasma beta for the jth species, and $V_{Ap} = (B_0^2/4\pi\rho_p)^{1/2}$ is the Alfvén veolocity with respect to the proton mass density $\rho_p = N_p m_p$.

Neglecting the oxygen ion dynamics in (3), and considering $\omega^2 \ll \frac{N_o}{N_p}\Omega_p\omega$, we get the helicon mode in multi-ion plasma

$$
\omega_0 = \pm\frac{N_p}{N_0}\left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right)\frac{k^2c^2}{\omega_{pp}^2}\Omega_p, \tag{4}
$$

which is very similar in structure to the dispersion relation for the usual helicon mode,

$$
\omega_H = \frac{k^2c^2}{\omega_{pe}^2}\Omega_e, \tag{5}
$$

in electron -proton plasma. In equation (4), the protons, which are lighter as compared to oxygen ions, play a role similar to that of electrons in the usual helicon modes (cf. (5)).

Now, we shall take into account the dynamics of the O^+ Ions, and look for an instability near the helicon mode frequency ω_0. Once again considering $\omega^2 << \frac{N_o}{N_p}\Omega_p\omega$, and writing $\omega = \omega_0 + \delta$, (3) simplifies to

$$
\delta^3 + [2(\omega_0 - kU_o) \pm \Omega_o]\,\delta^2 + (\omega_0 - kU_o)^2\,\delta + \left[-\frac{A_o k^2 V_{Ap}^2}{2R} + (\omega_o - kU_o)(\omega_0 - kU_o \pm \Omega_o)\right]\Omega_o = 0, \tag{6}
$$

where $R = (N_o m_o/N_p m_p)$ represents the relative oxygen ion mass density with respect to protons.

For the special case of isotropic plasma system, i. e., $A_e = A_p = A_o = 0$, (6) becomes a quadratic equation, and the helicon mode instability with RH polarization is excited by the O^+ ion beam provided

$$
\frac{kV_{Ap}}{R\Omega_o} < M < \left[\frac{kV_{Ap}}{R\Omega_o} + \frac{4\Omega_o}{kV_{Ap}}\right], \tag{7}
$$

where $M = U_o/V_{Ap}$ is the oxygen ion Alfvén Mach number where V_{Ap} is the Alfvén speed calculated using the proton mass density.

For a general anisotropic case, (6) can be easily solved numerically for the unstable modes. We solved (6) using *Mathematica* for both RH and LH polarized modes. We find that the helicon mode imitability occurred for the RH mode only. Therefore results for the real frequency, $\omega_r = (\omega_0 + Re\delta)$ and growth rate, $\gamma = Im\delta > 0$ for RH modes are shown in Figures 1-3 for the parameters relevant to the central plasmasheet (CPS) region where we have taken $\beta_{\|o} = 3.5$.

Figures 1a and 1b show that ranges of real frequencies and growth rate increase when A_o is increased. In Figure 1, growth rates could attain the maximum value for a certain value of the normalized wavenumber. But, in Figures 2 and 3, we have to truncate the curves for real frequency and the growth rates before the! latter could attain the maximum value, say γ_{max}/Ω_o. The truncation was necessary as the assumption of treating the: oxygen ions as cold, i.e.,

$$\eta_0^2 = \frac{R\Omega_o^2}{\beta_{\|o} k^2 V_{Ap}^2} \left| \frac{\omega}{\Omega_o} - \frac{MkV_{Ap}}{\Omega_o} + 1 \right|^2 \gg 1, \tag{8}$$

breaks down for values of the wavenumber kV_{Ap}/Ω_o larger than those shown in Figures 2 and 3.

Figures 2a and 2b show that an increase of M and R has destabilizing effects on the helicon mode. The range of excited real frequencies, growth rates, and of unstable ks are increased significantly by an increase in R from 1 to 10 (cf. curves 1, 2 and 3), and of M from 0.1 to 0.25 (cf. curves 3, 4 and 5).

Figures 3a and 3b show that positive (negative) values of proton anisotropy, A_p, lead to increased (decreased) values for real frequencies as wc]] as growth rates (cf. curves 1, 2 and 3). The effects clue to electron ansiotropy, A_e, were not found to be significant (not shown).

We may point out that the helicon mode is quite distinct from the right hand resonant beam instability [*Gary et al.*, 1985; *Tsurutani et al., 1985*]. Helicon mode instability is excited at, much lower (than the proton cyclotron) frequencies and at much longer wavelengths than the right hand beam resonant instability (typically slightly less than the proton Cyclotron frequencies). An important feature of the helicon mode instability is that it is excited at smaller Mach numbers (typically $M_o \sim$ 0.05- - 0.25 or so) than that required by resonant beam instability (typical $M \geq 1$).

3. DISCUSSION

Our analysis shows that tile presence of ionospheric O^+ ions in the inner central plasma sheet *(ICPS)* can excite helicon mode instability provided the beam Mach number lies in a certain range. The low-frequency long wavelength waves generated by this instability have right hand polarization. The ideal conditions for the excitation of helicon mode instability are the large values of parameters A., R, and M as seen from Figures 1, 2, and 3. Such conditions can be realised during growth phase of the substorms.

Observations indicate that, atleast during some occasions, O^+ ions can develop significant pressure anisotropy in the 1 CPS region[*Daglis et al., 1991; Lennartsson*, 1 994]. Computations by *Cladis and Francis* [1992] show that parameter A_0 can have values from 1 to 5 in the region X $\sim$ -10 R_E to -15 R_E within about two hours of the commencement of an enhanced convection event. Such large negative values can excite long wavelength nonresonant fire-l]osc imitability [*Lakhina*, 1995, 1996]. Here we have considered the nominal values of A_o = *0.1* to 2.0. Note that in this regime, the fire-llosc mode is stable. When the ionospheric-origin O^+ ion beam has initially large Mach number, the helicon mode instability will be excited first, However, if it saturates at rather low levels so that the Mach number of the beam is not reduced much, then there is a possibility of fire-l]osc mode getting excited by the O^+ ion beams.

The number density of O^+ ions in the inner central plasma sheet is quite variable. Therefore the parameter $R = N_o m_o / N_p m_p$ could vary over a wide range. We consider R =- 1- 10 as typical during during highly disturbed times [*Lennartsson and Shelley*, 1986; *Wilken et* al., 1995].

Measurements of O^+ ion flow velocity in the plasma sheet region are sparse. *Peterson et al.* [1981] have reported $U_p \sim 31$ km s^{-1} and $U_o \sim 43 \pm 60$ km s^{-1} with large uncertainties. Observations indicate flow velocities of O^+ ions varying between $U_o \sim$ (50 - 200) km s^{-1} in the magnetotail boundary layer and plasma lobe [*Candidi et* al., 1982], and $U_o \sim$ (20 120) km s^{-1} in the plasma sheet region [*Orsini et* al., 1985; *Stokholm et al.*, 1985] In the absence of simultaneous measurements of U_p, it is rather difficult to determine the relative drift speed between O^+ ions and protons in the plasma sheet region. Therefore, taking $|U_o - U_p| \approx$ 10- 60 km S^{-1} in the ICPS appears to be quite reasonable. Then, for B_0 = 10 nT and N_p = 0.5 cm^{-3}, we get typical Mach numbers M = 0.025 - 0.25 in the ICPS region.

Figures 1 -3 show that the range of excited real frequencies, growth rates, and unstable wavelengths, $\lambda = 2\pi/k$, are respectively $\omega_r = (0.1\ 0.5)\,\Omega_o$ = (1.0 5.0) mHz, γ = (0.1- 0.5) Ω_o= -(1.0 - 5.0) mHz, and $\lambda = V_{Ap}/(0.1 - 1.75)\Omega_o$ = (1 - 15) R_E for M = (0.01 0.25), R = 1 - 10, A_o = 0,1- 2.0, B_0 = 10 nT and N_p = 0.5 cm^{-3}. Hence the instability would preferentially excite low-frequency waves with wavelenghts $\sim$ (0.8 - 1 5) R_E in the ICPS. The typical c-folding time of the instability is about 3 to 15 minutes at wavelengths of $\lambda \approx$ 1 to 5 R_E, which is reasonably Snort. Therefore, these modes could attain saturation as the enhanced convection events may last for a few hours.

4. SUMMARY

The existence of large amplitude helicon modes driven by the free energy of the ionospheric-origin O^+ ion beams in the ICPS region may have some interesting consequences for the substorm processes. Firstly the large scale fluctuating 2 and y components, i.e., δB_z and δB_y, associated with the helicon modes could twist the equilibrium magnetic field into flux ropes. This gives an indication that the helicon modes may be playing some role in ***the*** processes related to oxygen ion bursts associated with multiple flux ropes in the distant magnetotail as observed by GEOTAIL [*Wilken et al.*, 1995]. Secondly, the large amplitude δB_z could produce localised minima in the z component of the 2]) equilibrium magnetotail magnetic field neat the neutral axis. Moreover, the low-frequency turbulence due to the helicon modes could scatter electrons trapped in the ICPS region, Both these factors would make these localized minima (separated by tile wavelength of the excited modes) to be the potential ***site*** for the excitation of the tearing mode instabilities which could lead to the onset of the expansion phase of the substorm. Thirdly, the helicon mode may be responsible for some of the low-frequency RH polarized ectromagnetic noise observed in the ICPS and [lasma sheet boundary layer [*Russell*, **19!32;** *Tsurutani et* d., 1985, 1987; *Bauer et al.*, 1995].

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Figure Captions

Figure 1: Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability driven by O^+ ions in the ICPS region for $M = U_o/V_{Ap} = 0.25$, $R = \rho_o/\rho_p = 1.0$, $A_e = A_p = 0$, and $\beta_{\|o} = 3.5$. The curves 1, 2,3, and4 are respectively for $A_o = (\beta_{\|o} - \beta_{\perp o}) = 0.1$,0.5, 1.0, and 2.0. For the parameters considered here as well as in Figures 2 and 3, the LH mode instability does not exist.

Figure 2: Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability driven by O^+ ions in the ICPS region for $A_e = A_p = 0$, and $A_o = 2.0$. For the curves 1, 2, and 3, $M = 0.05$, and $R = 1.0$, 5.0, and 10.0 respectively. For the curves 4 and 5, $R = 10.0$ and $M = 0.1$, and 0.2 respectively.

Figure 3: Variation of normalized real frequency (a), and growth rate (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability in the ICPS region for $R = 5.0$, and $M = 0.1$, $A_e = 0$, and $A_o = 2.0$, For the curves 1, 2, and 3, $A_p = -1.0$, 0.0,and 1.0 respectively.

Helicon mode

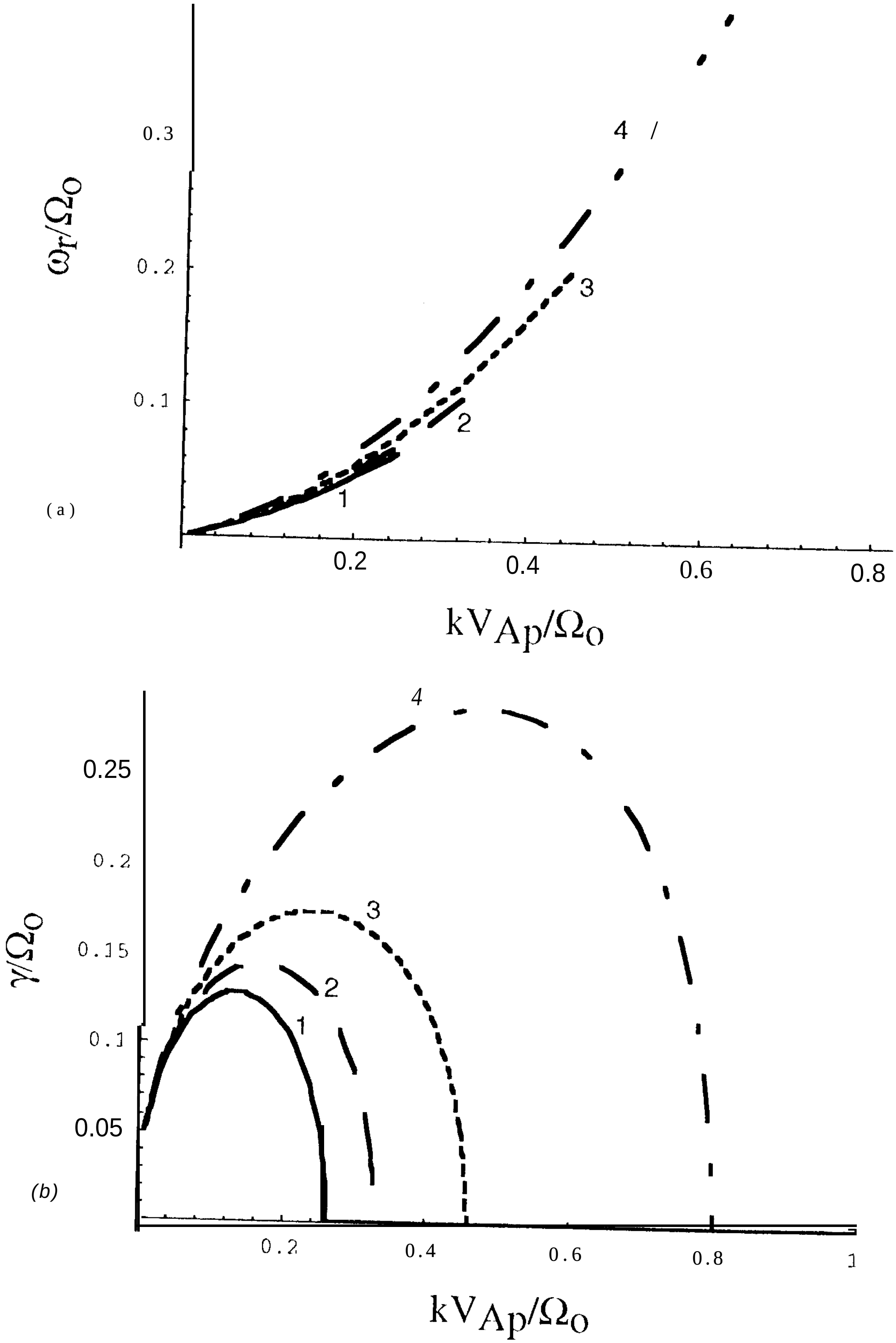

Fig. 1

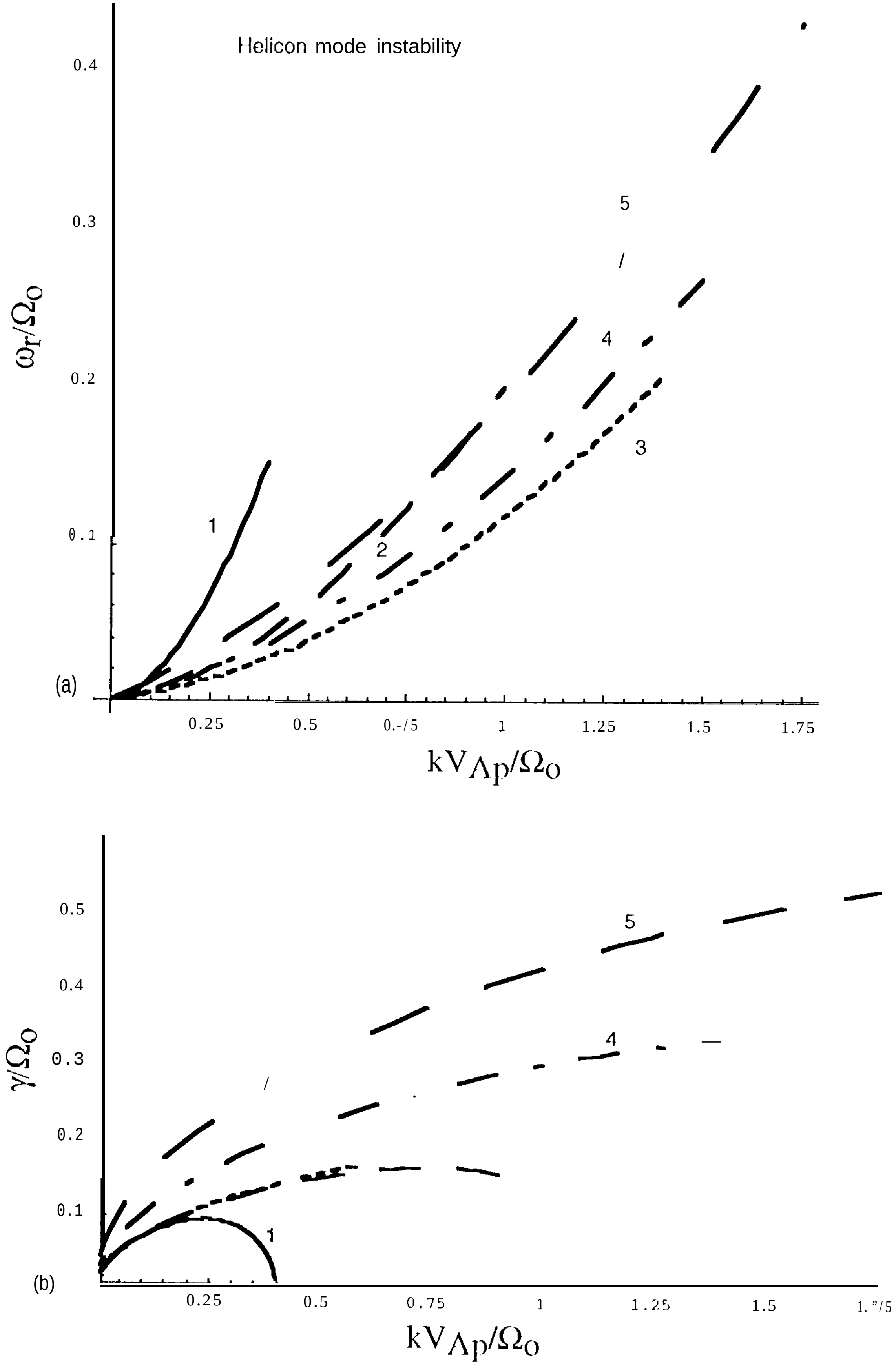
Helicon mode instability
ω_r/Ω_o
0.4
0.3
0.2
0.1
5
4
3
2
1
(a)
0.25
0.5
0.-/5
1
1.25
1.5
1.75
kV_{Ap}/Ω_o
γ/Ω_o
0.5
0.4
0.3
0.2
0.1
5
4
1
(b)
0.25
0.5
0.75
1
1.25
1.5
1."/5
kV_{Ap}/Ω_o

Fig. 2

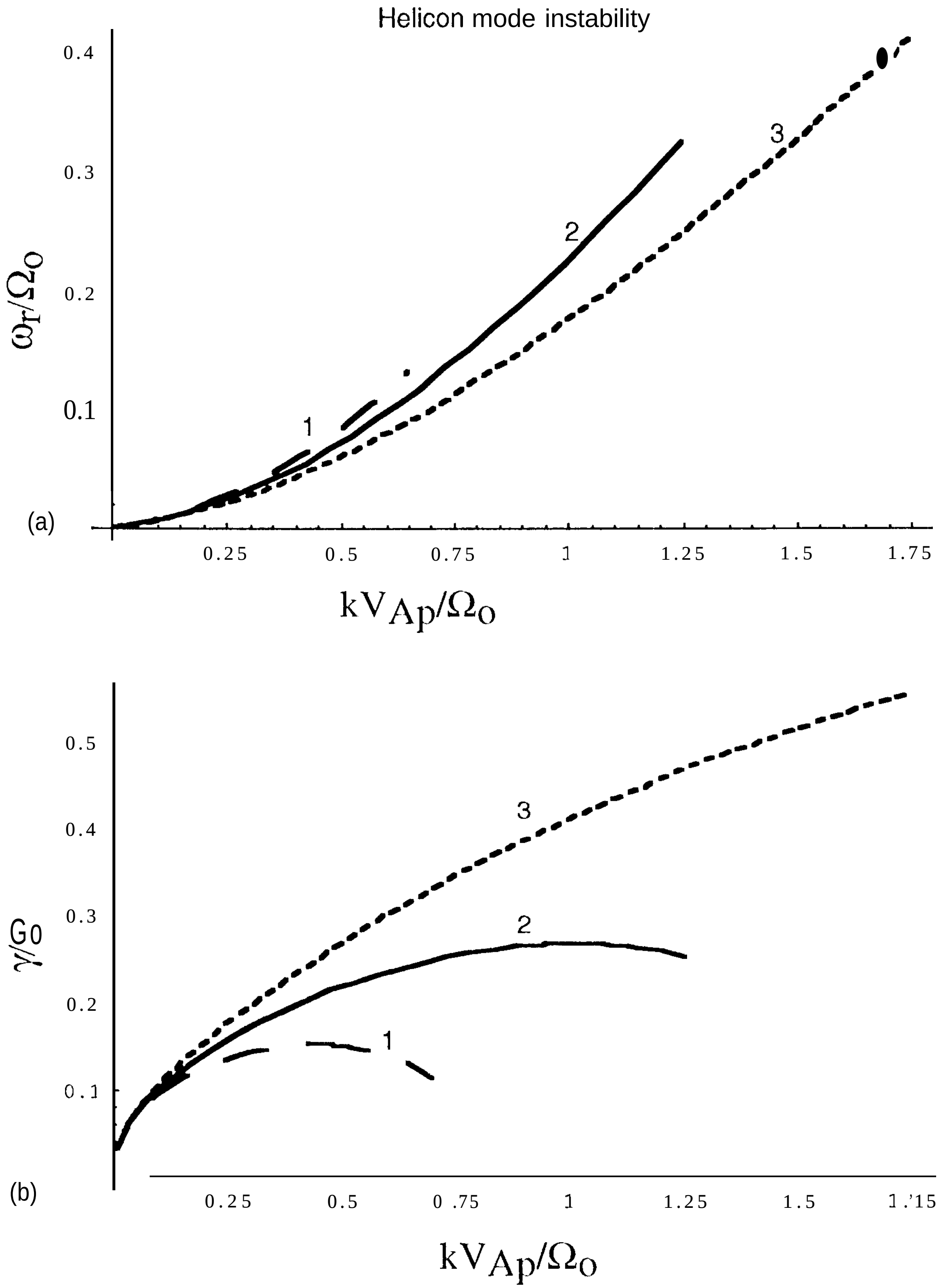
Helicon mode instability
0.4
0.3
0.2
0.1
ωr/Ωo
1
2
3
(a)
0.25
0.5
0.75
1
1.25
1.5
1.75
kVAp/Ωo
0.5
0.4
0.3
0.2
0.1
γ/Go
3
2
1
(b)
0.25
0.5
0.75
1
1.25
1.5
1.’15
kVAp/Ωo

Fig. 3